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Climate Change-Induced Pest and Disease Dynamics in Agricultural Crops: A Review

Santanu Kumar Patra[1*], Shahin Khan[2], Naval Kishore Meena[3], Vishal Prajapati[4]

[1]Assistant Professor, Department of Agricultural Extension, Faculty of Agriculture and Allied Sciences, C. V. Raman Global University, Bhubaneswar, PIN- 752054.

[2]Scientist, Department of Entomology, RVSKVV, ZARS Khargone M.P.

[3]Ph.D. Scholar, Department of Horticulture (Fruit Science), RCA, MPUAT, Udaipur-313001, Rajasthan

[4]M.Sc. Scholar, Department of Agronomy, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar- 848126

*Corresponding Author E-mail: santanuorissa3@gmail.com

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ABSTRACT

Climate change is reshaping pest and disease dynamics in agricultural ecosystems by altering temperature, precipitation, humidity, crop phenology, and host–pathogen interactions. Rising temperatures can accelerate pest development, expand geographic ranges, increase generations per season, and enhance the establishment of invasive species. Similarly, changing climatic conditions may favor the emergence, persistence, and transmission of fungal, bacterial, viral, and nematode pathogens. This review examines the impacts of climate variability and extreme weather events on crop pests and diseases, associated changes in outbreak patterns, and implications for agricultural productivity and food security. It also highlights climate-smart integrated pest and disease management strategies, emphasizing surveillance, resistant varieties, biological control, precision technologies, and adaptive forecasting approaches for resilient crop production.

Keywords: *Climate change; Crop pests; Plant pathogens; Range expansion; Climate-smart integrated pest management.*

INTRODUCTION

Feeding a growing human population depends on a narrow set of staple crops grown within an equally narrow envelope of climatic conditions. That envelope is now shifting faster than at any point in the recorded history of agriculture, and one of its least visible effects operates through living organisms rather than through heat or water stress alone. Biotic stressors are estimated to remove as much as 40 per cent of global crop production each year, with plant diseases alone costing the world economy more than US$220 billion annually and invasive insects a further US$70 billion (FAO, 2021).

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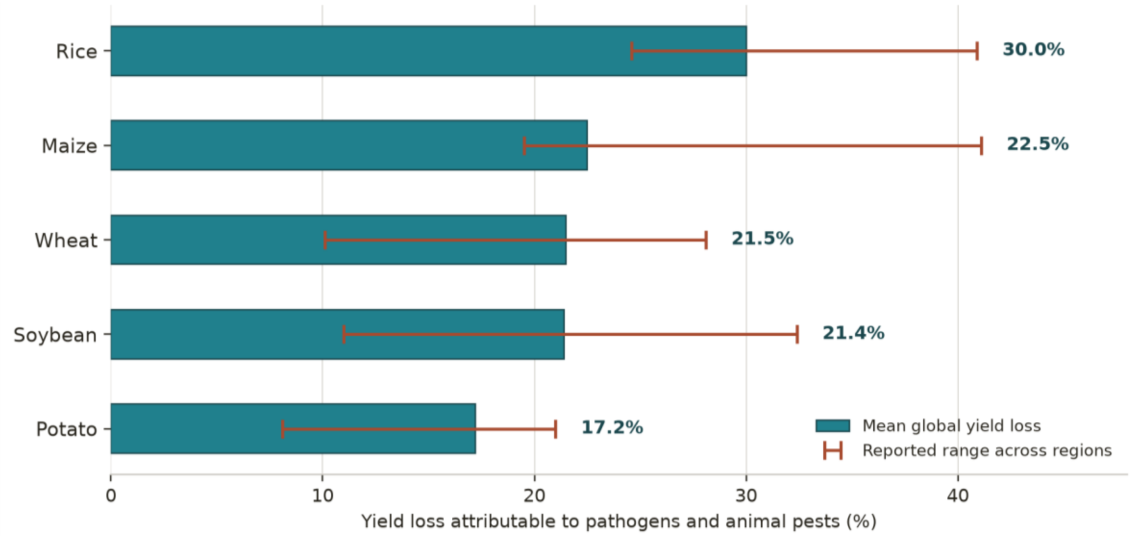

Fig.1. Mean global yield losses to pathogens and animal pests in five staple food crops, with the reported ranges across regions. Data from Savary et al. (2019)

A global expert elicitation covering 137 pests and pathogens on the five leading food crops placed mean yield losses at 30.0 per cent for rice, 22.5 per cent for maize, 21.5 per cent for wheat, 21.4 per cent for soybean and 17.2 per cent for potato, with the heaviest burden falling on food-deficit regions that can least absorb it (Savary et al., 2019). These baseline losses (Fig. 1) form the platform on which climate change now acts. The relationship between a changing climate and crop health is not simply one of more heat producing more pests. Climate acts simultaneously on the physiology and phenology of the pest or pathogen, on the physiology and defensive chemistry of the host plant, and on the natural enemies, microbial communities and human management practices that mediate the interaction. Analysis of documented observations since 1960 revealed that crop pests and pathogens have moved polewards at an average of 2.7 plus or minus 0.8 kilometres per year, a rate that tracks the pace of regional warming and implicates climate as the principal driver of redistribution (Bebber, Ramotowski, & Gurr, 2013). Metabolic scaling projections indicate that yield losses to insect pests in wheat, rice and maize will rise by 10 to 25 per cent for every degree Celsius of global mean warming, with temperate grain belts bearing the largest relative increases as insect populations move closer to their thermal optima (Deutsch et al., 2018). Modelling of 80 fungal and oomycete pathogens across 12 crops similarly projects the steepest increases in infection risk at higher latitudes, accompanied by a reshuffling of pathogen assemblages across the United States, Europe and China (Chaloner, Gurr, & Bebber, 2021). Equally important are the outcomes that are not captured by mean projections. Warming can undermine the temperature-sensitive resistance genes on which modern breeding depends (Velasquez, Castroverde, & He, 2018), decouple pests from their parasitoids (Bamisile et al., 2023), reduce the efficacy of chemical control (Matzrafi, 2019) and enable invasive species such as the fall armyworm, *Spodoptera frugiperda*, to colonise entire continents within a few seasons (Mendesil et al., 2023). The consequence is a plant health landscape that is not merely more hostile but substantially less predictable.

Climatic Drivers and Mechanistic Pathways

Four climatic drivers dominate the literature: rising mean and extreme temperatures, elevated atmospheric carbon dioxide, altered rainfall and humidity regimes, and an increased frequency of extreme events such as drought, storms and floods. Each operates through distinct physiological mechanisms, yet their effects converge on the same epidemiological outcomes (Fig. 2). Temperature governs the developmental rate, fecundity, survival, diapause behaviour and generation number of poikilothermic pests; carbon dioxide alters the nutritional and defensive chemistry of the host; moisture governs spore germination, infection windows and vector activity; and extreme events disrupt cropping calendars, damage plant tissue and create infection courts (Skendzic, Zovko, Zivkovic, Lesic, & Lemic, 2021). A comprehensive review of approaches to studying pathogens, insect pests and weeds under a changing global climate concluded that these drivers should be treated as interacting rather than additive, and that studies isolating a single variable systematically misrepresent field outcomes (Juroszek & von Tiedemann, 2012).

A further complication is the human feedback loop. Farmers respond to intensified pest pressure by increasing chemical inputs, altering sowing dates and shifting cropping patterns. Rising minimum daily temperatures across the mid-western United States were associated with measurably enhanced pesticide use in cultivated soybean along a latitudinal gradient, demonstrating that behavioural adaptation is already underway and carries its own environmental and economic costs (Ziska, 2014).

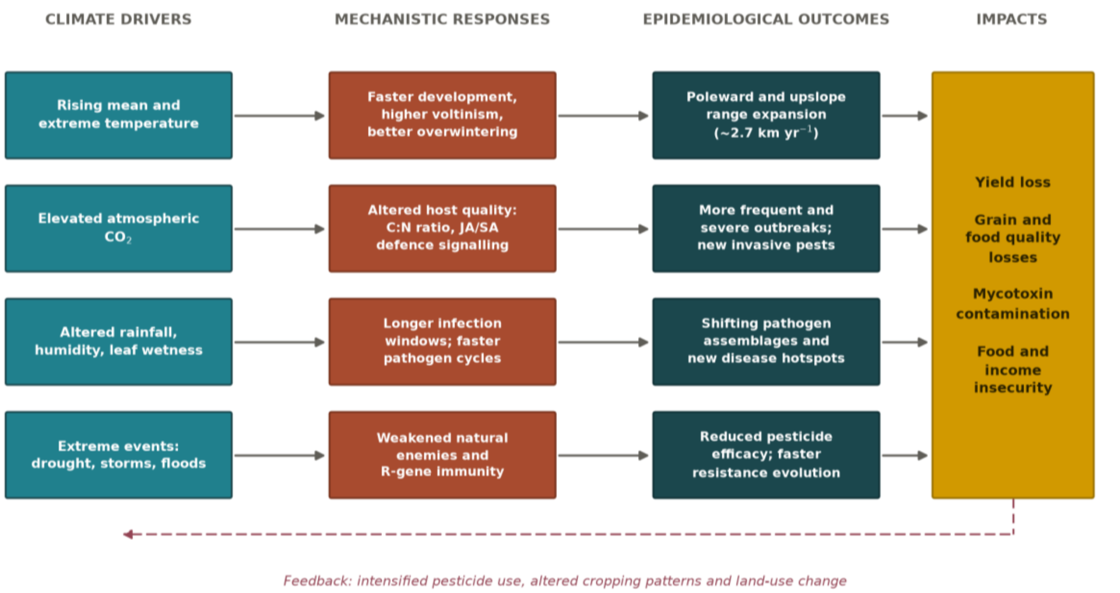

Fig.2. Conceptual framework linking climate change drivers to mechanistic responses, epidemiological outcomes and impacts on crop production, with the human management feedback loop indicated

Insect Pest Dynamics under a Warming Climate

Insects are ectotherms, and temperature is therefore the master variable controlling their population biology. Warming shortens development time, raises metabolic and reproductive rates, increases voltinism and improves overwintering survival, all of which act to expand both the size and the geographic reach of pest populations (Sharma, 2014; & Skendzic et al., 2021). Because population growth rate is a non-linear function of temperature, the direction of the effect depends on where a species currently sits relative to its thermal optimum. In temperate grain-producing regions, where most pests operate below their optimum, warming pushes populations towards peak performance; in already hot tropical regions, further warming may push some species beyond their upper thermal limits (Riegler, 2018).

This asymmetry explains the geography of the most widely cited projection in the field. Coupling insect metabolic and demographic responses to temperature with climate scenarios, Deutsch et al. (2018) estimated that insects already consume 5 to 20 per cent of major grain crops and projected that losses would rise by 10 to 25 per cent per degree of warming, with the largest absolute increases concentrated in the wheat-growing regions of Europe, North America and China (Fig. 3). The projection has been productively contested: laboratory-derived metabolic curves may not extrapolate cleanly to field agroecosystems, where natural enemies, host plant variation and management intervene (Parmesan, Hanley, & Singer, 2018), and current loss-modelling tools frequently fail to capture non-linear physiological thresholds and interactions with elevated carbon dioxide (Tonnang, Sokame, Abdel-Rahman, & Dubois, 2022).

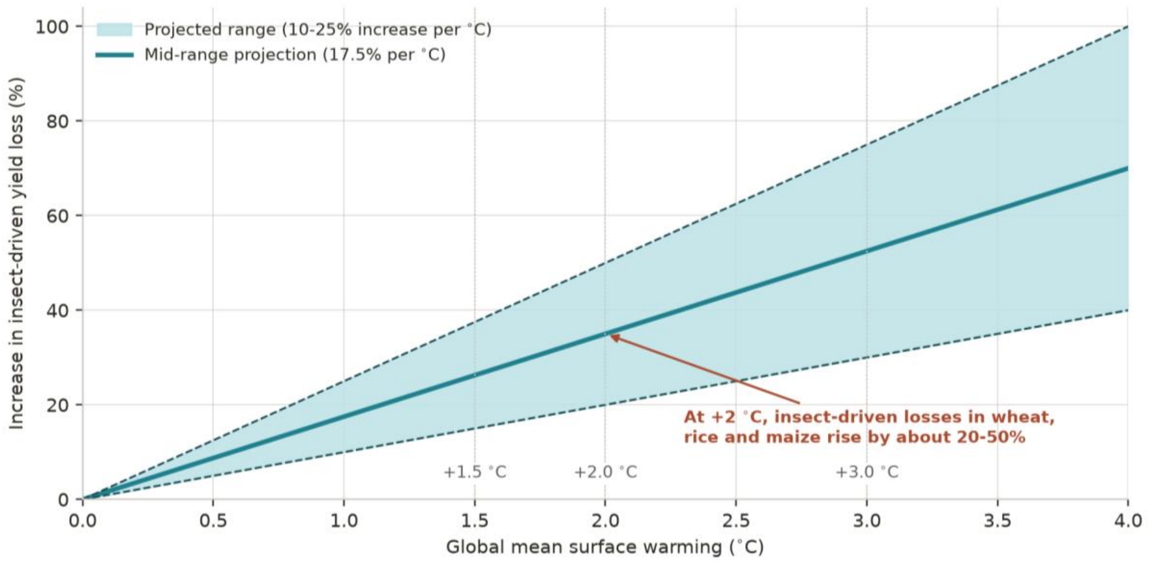

Fig.3. Projected increase in insect-driven yield losses in wheat, rice and maize as a function of global mean surface warming. The shaded band shows the projected range of 10 to 25 per cent additional loss per degree Celsius reported by Deutsch et al. (2018)

Range redistribution is the second major signature of warming. Beyond the mean poleward shift of 2.7 kilometres per year, the rate is strongly taxon-dependent: wind-dispersed fungal spores and migratory insects advance fastest, while soil-borne and low-mobility organisms lag behind, a pattern with clear implications for surveillance prioritisation (Bebber, 2015). Climate suitability is not the only control. Analyses of global pest distributions show that trade volume and economic connectivity explain as much variation in the accumulation of non-native pest species as climatic similarity between source and recipient regions (Bebber, Gurr, & Holmes, 2014; Bebber, Smith, Gurr, & Holmes, 2014). Climate change therefore expands the set of places where an introduced organism can establish, while trade determines how quickly it arrives.

Elevated Carbon Dioxide and Plant-Insect Interactions

Rising atmospheric carbon dioxide affects herbivores mainly indirectly, through the host plant. The classical explanation invoked dilution of leaf nitrogen, prompting compensatory feeding as insects consume more tissue to meet nutritional requirements, but hormonal signalling matters at least as much. Elevated carbon dioxide tends to down-regulate jasmonic acid and ethylene-dependent defences while elevating salicylic acid-mediated responses, weakening the pathways that protect plants against chewing herbivores (Zavala, Gog, & Giacometti, 2019). In one controlled study, the relative growth rate of *Helicoverpa armigera* increased by approximately 66 per cent under elevated carbon dioxide, in association with jasmonic acid concentrations about 56 per cent lower than under ambient conditions, while declines in leaf nutritional quality were minimal, indicating that impaired defence signalling rather than nutrition drove the response (Hall, Waterman, & Johnson, 2020).

Responses are nonetheless species- and system-specific rather than uniformly favourable to pests. In bell pepper, reduced leaf nitrogen under elevated carbon dioxide produced a 37 per cent decrease in the fecundity of the green peach aphid, *Myzus persicae*, while altering its feeding behaviour and its capacity to transmit plant viruses (Fereres, Moreno, Dader, & Trebicki, 2016). Changes in melon phytochemistry impaired the growth and reduced the body weight of the cotton aphid, *Aphis gossypii* (Moreno-Delafuente et al., 2021). For pathogens, the salicylic acid to jasmonic acid shift generally suppresses biotrophic infection while increasing susceptibility to necrotrophic fungi (Li & Ahammed, 2023). The broader conclusion is that carbon dioxide, warming and altered precipitation are jointly resetting plant-insect interactions, and that their combined effects may be additive, synergistic or antagonistic depending on the specific pairing (DeLucia, Nabity, Zavala, & Berenbaum, 2012).

Plant Pathogens and the Climate-Modified Disease Triangle

Plant disease requires the coincidence of a susceptible host, a virulent pathogen and a conducive environment, and climate change is unusual among agricultural stressors in acting on all three vertices of this triangle at once (Fig. 4). It alters host phenology and immunity, accelerates pathogen life cycles and evolution, and redefines the temperature, humidity and leaf-wetness conditions that determine infection windows (Juroszek & von Tiedemann, 2012). Pathogen ranges, disease incidence and disease severity are all shifting, and eco-evolutionary theory needs to be incorporated into predictive frameworks (Singh et al., 2023).

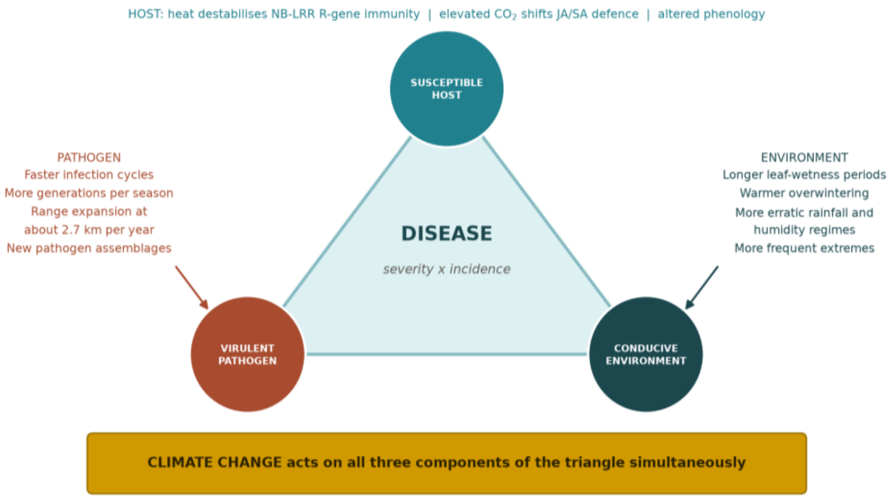

Fig.4. The climate-modified disease triangle. Warming, elevated carbon dioxide and altered moisture regimes simultaneously affect host susceptibility, pathogen aggressiveness and environmental conduciveness, jointly determining disease severity and incidence

Evidence from individual pathosystems illustrates the diversity of outcomes. Black Sigatoka of banana, caused by *Pseudocercospora fijiensis*, showed a median increase in infection risk of 44.2 per cent across Latin American and Caribbean growing regions since the 1960s (Bebber, 2019). Climate reanalysis modelling helped explain the severe Colombian coffee leaf rust epidemic of 2008 to 2011 as partly attributable to shifting temperature and rainfall patterns (Bebber, Castillo, & Gurr, 2016). Elevated air temperature is projected to enhance the future epidemic risk of *Phytophthora infestans*, the cause of potato and tomato late blight (Wu, Zhan, Yang, Zhao, & Wang, 2022). Wheat stem rust, largely absent from Europe for six decades, re-emerged after 2016 with epidemics on durum and bread wheat across southern, central and western Europe (Berlin et al., 2022), while yellow rust populations in France display temperature-specific local adaptation, demonstrating that rust pathogens can evolve in step with regional thermal regimes (Bahri et al., 2011).

Regional reviews confirm the pattern for wheat and maize, projecting altered risk zones for Fusarium head blight, septoria leaf blotch and the rusts as European temperature and precipitation regimes shift, and a movement of tropical maize pathogens into temperate areas (Juroszek & von Tiedemann, 2013a, 2013b). Food safety is affected alongside yield: modelling of aflatoxin contamination under warming of two and five degrees Celsius indicates that parts of central and northern Europe historically at low risk may become newly vulnerable (Battilani et al., 2016; Leggieri, Battilani, & Toscano, 2021). Predictive capability remains limited by insufficient data on the combined effects of elevated carbon dioxide, temperature and drought on fungal toxin production (Medina, Akbar, Baazeem, Rodriguez, & Magan, 2017).

Insect Vectors, Invasive Species and Outbreak Pests

Many of the most damaging plant diseases are transmitted by insects, so vector responses to climate are epidemiologically decisive. Climatic chamber simulation of the projected central European climate for 2061 to 2070 shortened the development time of the MED biotype of *Bemisia tabaci*, a globally important whitefly vector of plant viruses, by about 40 per cent and raised its fecundity by roughly a third, implying much faster population build-up in currently temperate regions (Milenovic, Eickermann, Junk, & Rapisarda, 2023). Mechanistic thermal-niche modelling of huanglongbing, or citrus greening, indicates that transmission between citrus hosts and the psyllid vector *Diaphorina citri* is possible between 16 and 33 degrees Celsius and peaks near 25 degrees Celsius, with emerging suitability in currently unaffected regions (Taylor et al., 2018). Climatic suitability for the parasitoid *Tamarixia radiata*, the principal biological control agent of that vector, is itself projected to shift, meaning that pest and control agent may not move together (Aidoo et al., 2022).

Invasive species provide the most visible demonstrations of a destabilised plant health system. The fall armyworm, *Spodoptera frugiperda*, was first reported as an invasive alien pest in West and Central Africa in 2016 and spread across the continent and into Asia within a few seasons, threatening maize-based food security across two continents (Togola, Goergen, Tamo, Kumar, & Sankung, 2016; & Mendesil et al., 2023). A survey across five African countries found that most smallholders responded with chemical pesticides, frequently without adequate knowledge of safe or effective application, exposing serious gaps in extension provision (Tambo et al., 2020). Reviews of climate-responsive management conclude that early reliance on insecticides was often ineffective and accelerated resistance, whereas agro-ecological practices combined with parasitoids and entomopathogens produced more durable suppression (Zanzana, Dannon, Sinzogan, & Toffa, 2024).

The desert locust upsurge of 2019 to 2020, the worst in East Africa for decades, has been linked to anomalously wet conditions associated with unusual Indian Ocean cyclone activity that created favourable breeding conditions across the Horn of Africa and the Arabian Peninsula (Salih, Baraibar, Mwangi, & Artan, 2020). Interestingly, longer-term modelling suggests that the potential habitat of *Schistocerca gregaria* may contract by the late twenty-first century even as short-term outbreak risk rises with anomalous weather (Zheng et al., 2021), a reminder that mean-state projections and event-driven risk can diverge. The tomato leaf miner, *Tuta absoluta*, has undergone a documented niche shift during its global invasion, which complicates risk assessments that assume static climatic tolerances (Marchioro & Krechemer, 2024).

Erosion of Host Resistance, Biological Control and Pesticide Efficacy

Three lines of defence that underpin modern crop protection are each weakened by warming. The first is host plant resistance. Many responses mediated by nucleotide-binding leucine-rich repeat receptor proteins are temperature-sensitive and lose efficacy above species-specific thresholds, often between 28 and 30 degrees Celsius (Hua, Qian, & Zhu, 2010; & Hua & Dong, 2022). Because heat suppresses resistance-protein signalling independently of the pathogen, varieties bred around single major genes may fail in the field without any shift in pathogen virulence, and growth-immunity trade-offs further constrain breeding options (Venkatesh & Kang, 2019).

The second is biological control. Hosts and parasitoids do not necessarily respond to warming at the same rate, creating scope for phenological mismatch and reduced suppression (Bamisile et al., 2023). Interannual climate variation alone alters host-parasitoid synchrony, so increased variability, not just higher means, can destabilise these interactions (Jennings, Duan, Wetherington, & Shrewsbury, 2017), and heat combined with drought reduces parasitoid effectiveness beyond what either stressor causes alone (Romo & Tylianakis, 2013). Responses are not uniformly negative: some natural enemies retained their control potential under short-term exposure to future climate conditions (Guyer et al., 2021).

The third is chemical control. Altered temperature and humidity regimes reduce pesticide efficacy, compounding the direct effects of warming (Matzrafi, 2019), and warming also accelerates resistance evolution. An expanded overwintering range in a globally significant pest was associated with pesticide resistance approximately 158 times higher in overwintering than in seasonally migrant populations, because year-round persistence exposes successive generations to continuous selection (Ma et al., 2021). Rising temperature increased both the level and the spatial differentiation of fungicide tolerance in a major pathogen population (Lurwanu et al., 2021), and enhanced detoxification enzyme activity in weeds, raising herbicide-resistance risk independently of herbicide use (Matzrafi, Seiwert, Reemtsma, Rubin, & Peleg, 2016). Thermal stress is now recognised as a general contributor to the evolutionary origins of pesticide resistance (Dixon, Bass, Hawkins, & Neve, 2019).

Modelling, Forecasting and Early Warning

Anticipating where pests and pathogens will occur is central to adaptation, and two modelling traditions dominate. Mechanistic niche models such as CLIMEX derive climatic suitability from measured physiological tolerances, while correlative models such as MaxEnt infer it from occurrence records. The two often diverge, with mechanistic models typically indicating broader potential ranges, and are increasingly treated as complementary rather than competing (Hayat, Shi, Wu, Rizwan, & Haider, 2024). Incorporating a CLIMEX-derived ecoclimatic index as a predictor within a MaxEnt framework improved performance over either method alone (Neven, Kumar, & Yee, 2014), and risk modelling for the spotted stem borer, *Chilo partellus*, demonstrated the value of integrating irrigation and cropping-pattern data into climate matching (Kriticos, van den Berg, Ota, Yonow, & Hutchison, 2016).

For diseases, weather-driven mechanistic models such as that developed for septoria tritici blotch of wheat show how humidity and temperature variables can be embedded in operational, real-time risk forecasting (Chaloner, Fones, Varma, Bebber, & Gurr, 2019). At larger scales, remote sensing has proved central to identifying desert locust breeding areas before outbreaks develop (Kimathi et al., 2020). Reviews of the field emphasise that linking mechanistic disease models to climate scenarios, rather than relying on static historical risk maps, is essential under non-stationary climatic conditions (Juroszek & von Tiedemann, 2015), and that genomic surveillance and diagnostic sensor networks should form part of a global early-warning architecture (Ristaino et al., 2021).

Climate-Smart Adaptation and Management

Adaptation requires more than incremental adjustment of existing practice. The Sixth Assessment Report projects that around 10 per cent of current cropland and livestock-rearing area will become climatically unsuitable by 2050, rising above 30 per cent by 2100 under a high-emissions pathway against less than 8 per cent under strong mitigation, and identifies cultivar improvement, agroforestry, diversification and community-based adaptation as effective responses (IPCC, 2022). Preventive mitigation and biosecurity are urgently required, particularly in cooler temperate, boreal and subtropical regions where pest risk is rising fastest (Hurley et al., 2022).

Climate-smart integrated pest management provides a workable organising framework (Fig. 5), combining surveillance and prediction, prevention through resistant cultivars and cultural practice, and suppression through biological control and judicious pesticide stewardship. Synthesis of 58 pest management projects conducted in tropical Africa over 55 years found that climate-smart plant health interventions raised yields while reducing emissions relative to conventional pesticide regimes (Neuenschwander, Borgemeister, De Groote, Saethre, & Tamo, 2023). Adoption, however, is governed as much by institutional support, extension access and land tenure security as by agronomic efficacy (Gaitu et al., 2022), and farmers who monitor outcomes and adapt their practices cope better with unpredictable pest pressure than those following fixed rules (Rebaudo & Dangles, 2015). Broader reviews call for transdisciplinary research, capacity building and spatially explicit management of multiple interacting pests (Bernal et al., 2024; Rodriguez-Saona, Zalucki, Desneux, Han, & Liu, 2024).

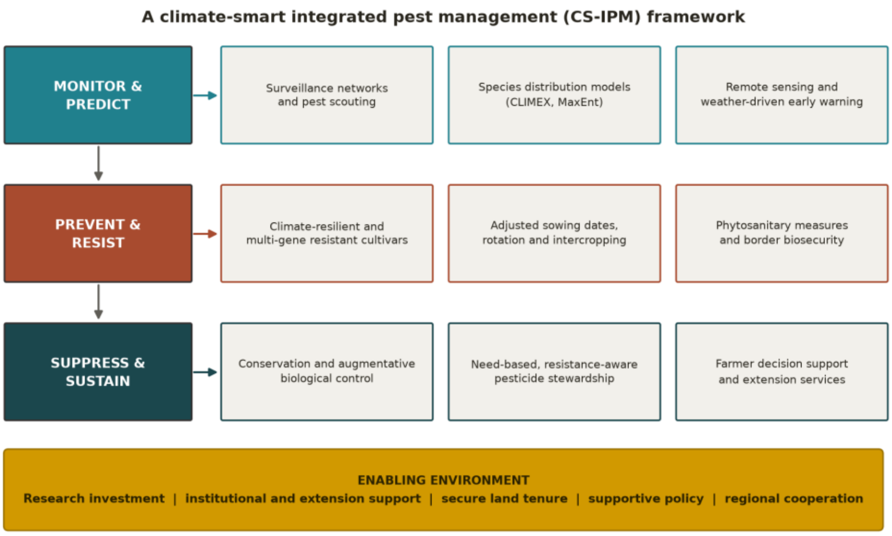

Fig.5. A three-tier climate-smart integrated pest management framework, showing the monitoring, prevention and suppression components and the enabling institutional environment required for adoption

Evidence from South Asia underlines the urgency. Work on host, pathogen and disease adaptation in arid and semi-arid regions projects that currently minor pest species could attain major pest status, with potential yield losses of up to 40 per cent in South Asian agriculture by 2100 under continued warming (Pathak, Singh, Tak, & Gehlot, 2018). Surveys of farm households in East Africa and South Asia found heightened crop pest and disease incidence among the most commonly reported climate-induced risks (Aryal, Sapkota, Rahut, Marenya, & Stirling, 2021), and tea growers in Assam identified pest and disease pressure as one of the most tangible impacts of a changing climate (Baruah & Handique, 2021). Analyses of Indian cereal production stress the need for proactive, climate-adaptive policy (Singh, Arora, & Babu, 2024), while projections that South Asian cropland exposure to drought could rise by up to 49.2 per cent by mid-century indicate that pest pressure will compound rather than substitute for abiotic stress (Su et al., 2024).

Research Gaps and Future Perspectives

Four gaps recur across the literature. First, most experimental work manipulates a single climatic variable, whereas field outcomes are determined by interactions among temperature, carbon dioxide, moisture and extremes. Second, long-term field validation of model projections remains scarce, limiting confidence in quantitative loss estimates (Parmesan et al., 2018). Third, the tropics and subtropics, where vulnerability is greatest, remain underrepresented relative to temperate systems. Fourth, evolutionary responses of pests, pathogens and natural enemies to rapid climatic change are rarely incorporated into risk models, even though thermal adaptation has already been demonstrated in rust populations (Bahri et al., 2011). Addressing these gaps will require multi-factor experiments, sustained regional surveillance networks and closer coupling between eco-evolutionary theory and applied forecasting.

CONCLUSION

Climate change is not adding a new stressor to crop production so much as reorganising an existing one. The evidence reviewed here shows a consistent set of signals: crop pests and pathogens are moving polewards at roughly 2.7 kilometres per year, insect-driven losses in the major cereals are projected to rise by 10 to 25 per cent for every degree of warming, pathogen infection risk is increasing most steeply at higher latitudes, and elevated carbon dioxide is quietly rewiring the defensive chemistry of host plants. At the same time, the three pillars of crop protection are weakening in parallel, as heat destabilises resistance-gene immunity, climatic variability disrupts host-parasitoid synchrony, and warming both reduces pesticide efficacy and accelerates resistance evolution. Against a baseline in which pests and pathogens already remove roughly a fifth to a third of the major staple harvests, these changes carry substantial food security consequences, concentrated in the tropical and South Asian regions least equipped to absorb them. Simple intensification of chemical control is self-defeating. What is required instead is climate-smart integrated pest management built on predictive modelling and surveillance, durable multi-gene resistance, conservation of natural enemies, and phytosanitary systems designed for a world in which pest geography is no longer stationary. Delivering this at scale is as much an institutional and policy challenge as a scientific one.

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All authors reviewed and approved the manuscript.

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